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REDUCING PEAK POWER IN AUTOMATED WEAPON LAYING

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U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

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INTRODUCTION

In artillery, the process of aiming a weapon is referred to as gun laying. Gun laying involves a set of actions to align the axis of a gun barrel so that it points in the required direction. This alignment is specified relative to the horizontal and vertical planes. A gun is traversed in the horizontal plane and elevated in the vertical plane to range it to the target. The traverse and elevation values make up the aiming portion of the firing solution. In an automated weapon system, the rotation of these two axes is performed using actuators.

A typical motion profile follows the velocity versus time graph shown in figure 1. An object will accelerate at a given rate up to a maximum velocity and, after a period of time, will decelerate at a given rate until stopping at the target position. In this figure, displacement (or distance) is represented as the area under the curve, and acceleration is represented as the slope of the line. In some cases, the required distance may be short enough that the maximum velocity is never reached. This condition is shown in figure 2. In the case of laying a gun, there would be a separate profile for both the traverse and elevation axis. Distance, velocity, and acceleration are replaced by angle, angular velocity, and angular acceleration.

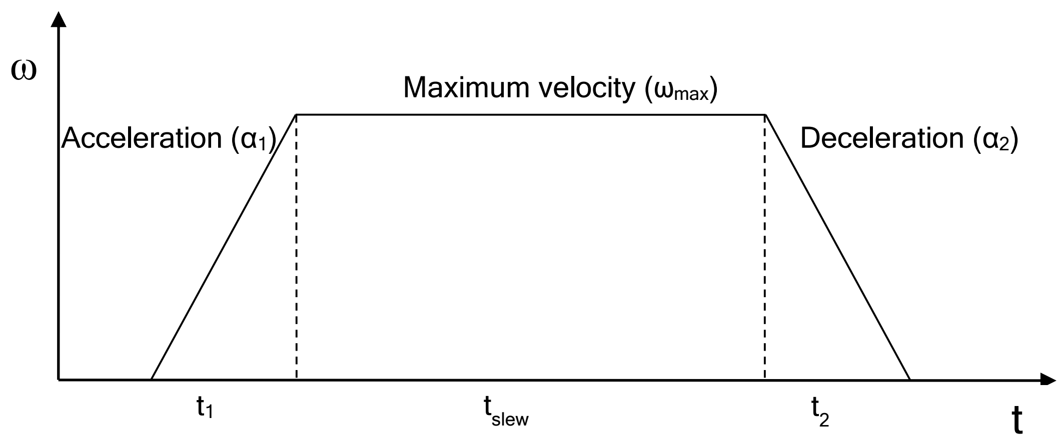

Figure 1
Trapezoidal motion profile

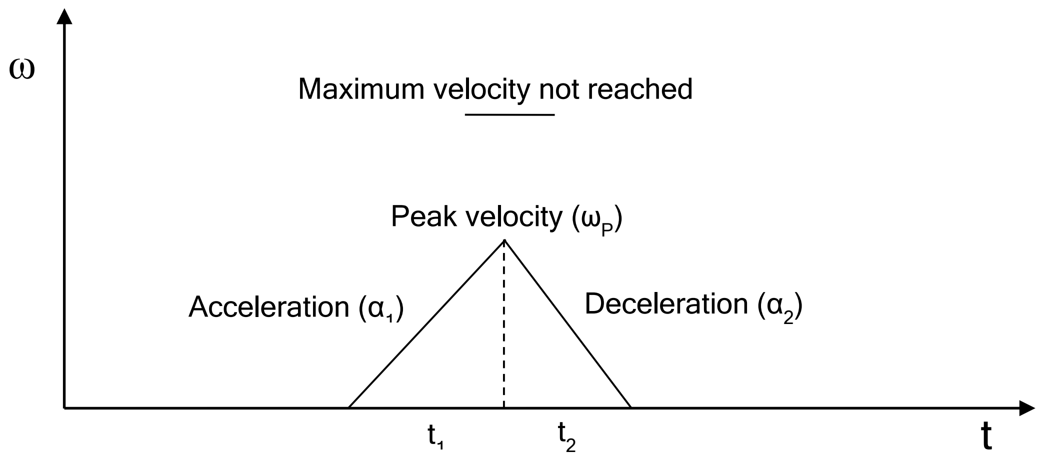

Figure 2
Triangular motion profile

Typical actuator controllers are configured by setting acceleration and maximum velocity values. When commanded to move a given displacement, the controller executes a motion profile using those stored values. The values used are determined based on a number of factors including available power, maximum motor speed, maximum safe slewing speeds, peak available motor torque, and desired maximum laying time. These precalculated values guarantee that the system remains within safe operating limits while executing within the required time for a worst case targeting situation. If these values are not optimized, most laying motions will result in one axis arriving at its commanded angle before the other. Since the weapon is only layed once both axes are in place, there is an unnecessary amount of power spent accelerating and decelerating the closer axis. By reducing the acceleration and deceleration rates of the closer axis to follow a motion profile that arrives at its target at the same time as the further axis, one can reduce peak power and the forces imparted on the system.

METHODS, ASSUMPTIONS, AND PROCEDURES

Conventions and Variable Definitions

Before describing the formulas to solve the aforementioned problems, it is necessary to define conventions and variables. Table 1 defines the variables used in the subsequent calculations.

Table 1
Variable definitions

Variable	Definition
θ	Displacement angle
θ_1	Displacement while accelerating to peak velocity
θ_2	Displacement while accelerating from peak velocity to 0
θ_{slew}	Displacement while slewing at a constant velocity
ω_{max}	Maximum angular velocity setpoint
ω_P	Peak angular velocity of triangular motion profile
α_1	Angular acceleration used to increase velocity
α_2	Angular acceleration used to decrease velocity (decelerate)
t_1	Time spent accelerating to peak velocity
t_2	Time spent accelerating from peak velocity to 0
t_{slew}	Time spent slewing at a constant velocity
t_{target}	Target amount of time to complete motion in

Fundamental Equations

Kinematics equations describe the motion of objects in space. The following equations will be used throughout this report and are valid for constant angular acceleration in one dimension.

$$\theta = \theta_0 + \omega_0 t + {}^1\!/_2\, \alpha t^2 \tag{1}$$

$$\omega = \omega_0 + \alpha t \tag{2}$$

$$\omega^2 = {\omega_0}^2 + 2\alpha(\theta - \theta_0) \tag{3}$$

When working with velocity versus time graphs, it is often simpler to solve for zero by thinking in terms of the area under the curve. For periods of constant velocity, this is a rectangle whose area is equal to

$$\theta = \omega t \tag{4}$$

For a period of constant acceleration, there are three equivalent equations that can be used depending on the variables of interest. These equations treat the period of deceleration as if they were accelerating (hence the absolute value for acceleration). The assumption is that the period of acceleration will always either begin or end at a velocity of zero.

$$\theta = {}^1\!/_2\, \omega t = {}^{\omega^2}\!/_{2|\alpha|} = {}^1\!/_2\, |\alpha| t^2 \tag{5}$$

Calculating Time Periods

The first step in calculating time periods is determining the shape of the profile. Given θ, ω_{max}, α_1 and α_2 it can be determined whether a trapezoid or triangle shaped motion profile will be used. This is done by first assuming a triangular profile and calculating the peak velocity (ω_P) attained using only the α_1 and α_2. The angle to travel can be broken into two parts. The first occurs during the acceleration period and the second during the deceleration period. For the purpose of finding the angle, the value of α_2 can be treated as positive (area under the curve of a triangle).

$$\theta = \theta_1 + \theta_2 = {}^1\!/_2\, \alpha_1 t_1^2 + {}^1\!/_2\, |\alpha_2| t_2^2 \tag{6}$$

The velocity starts at zero and rises to a peak value during t_1 (eq. 7). During t_2 it starts at the same velocity and ends at zero (eq. 8). These two formulas are set equal to each other in equation 9 and then solved for t_2 in equation 10. Note that the negative value of α_2 results in a positive value for t_2.

$$\omega = \omega_0 + \alpha_1 t_1 = 0 + \alpha_1 t_1 = \alpha_1 t_1 \tag{7}$$

$$\omega_{final} = 0 = \omega_0 + \alpha_2 t_2 \Rightarrow \omega = -\alpha_2 t_2 \tag{8}$$

$$\alpha_1 t_1 = -\alpha_2 t_2 \tag{9}$$

$$t_2 = -\frac{\alpha_1 t_1}{\alpha_2} \tag{10}$$

The result of plugging the equation for t_2 into equation 6, solving for t_1, and simplifying is

$$t_1 = \sqrt{\frac{2\theta}{{\alpha_1^2}/{|\alpha_2|} + \alpha_1}} \tag{11}$$

Multiplying this value by the absolute acceleration rate of α_1 provides the peak angular velocity for a triangular motion profile.

$$\omega_P = \alpha_1 t_1 \tag{12}$$

If ω_P is less than ω_{max} , the motion profile is triangular. Otherwise, the motion profile is trapezoidal.

For a triangular profile, all the work has already been completed with t1 and t2 represented by equations 10 and 11 respectively. Since ω_P is never reached, t_{slew} is set to zero.

If the shape of the motion profile is trapezoidal, the times can be solved for using equations 2 and 5.

$$t_1 = \frac{\omega_{max}}{\alpha_1} \tag{13}$$

$$t_2 = \frac{\omega_{max}}{\alpha_2} \tag{14}$$

$$t_{slew} = \frac{\theta - \theta_1 - \theta_2}{\omega_{max}} = \frac{\theta - {}^{\omega_{max} t_1}\!/_2 - {}^{\omega_{max} t_2}\!/_2}{\omega_{max}} = \frac{\theta}{\omega_{max}} - \frac{t_1 + t_2}{2} \tag{15}$$

Calculating New Acceleration Values

Once the time periods have been calculated, it can be determined which axis takes longer to travel using the given acceleration and maximum speed values. The faster axis can then be slowed down to match the travel time of the slower axis. The new target travel time will be referred to as t_{target}. The first step in calculating the values for the new motion profile is to determine if the solution profile will take the form of a trapezoid or a triangle. To do so, the change in time between t_{target} and t_{total} is calculated.

$$\Delta t = t_{target} - t_{total} \tag{16}$$

If Δt is less than t_{slew}, the motion profile of the solution is trapezoidal. The rationale behind this is demonstrated in figures 3 and 4. As α_1 and α_2 are decreased (the slopes are flattened), an equal amount of angular displacement (area) is both added and removed, keeping the total displacement the same. However, at some point, the acceleration removal results in a total erosion of the available t_{slew} time therefore requiring a triangular profile solution. Obviously, if the initial profile shape is triangular, t_{slew} is zero and the solution will always be triangular as well.

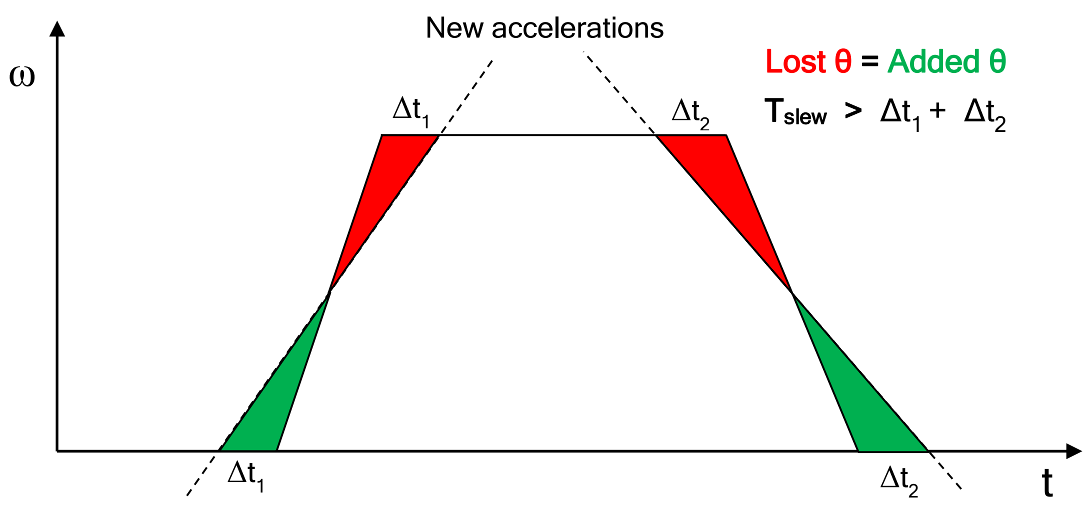

Figure 3
Trapezoidal time adjustment

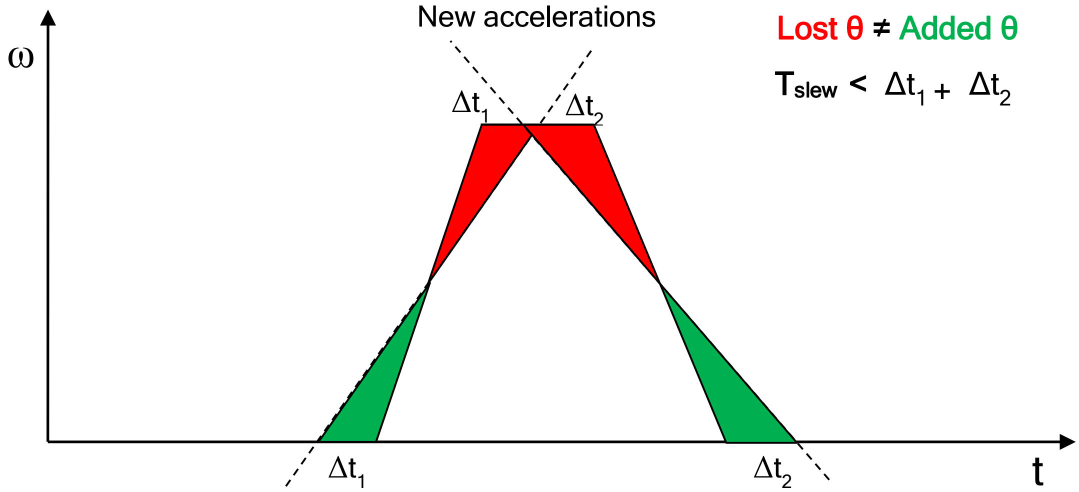

Figure 4
Invalid trapezoidal time adjustment

Once the shape of the motion profile is determined, use the appropriate set of calculations to determine the new values of α_1 and α_2.

For both profiles, it is assumed that the ratio between acceleration and deceleration will be maintained, resulting in equation 17. Therefore, written as

$$\frac{\alpha_1}{\alpha_2} = \frac{\alpha_{1new}}{\alpha_{2new}} \tag{17}$$

Triangular Profile

For a triangular profile, there is a known displacement angle θ and a given target time t_{target}. New acceleration values are being calculated, which can be called α_{1new} and α_{2new}. The t_{1new} and t_{2new} can be defined as the new times spent accelerating and decelerating. The sum of these is the total target time.

$$t_{target} = \mathrm{t}_{1new} + \mathrm{t}_{2new} \tag{18}$$

Using equations 10, 17, and 18, t_{1new} in terms of t_{target} can be solved as

$$t_{1new} = \frac{\alpha_2}{(\alpha_2 - \alpha_1)} t_{target} \tag{19}$$

Substituting equation 19 into equation 2 results in

$$\omega_P = \alpha_{1new} \frac{\alpha_2}{(\alpha_2 - \alpha_1)} t_{target} \tag{20}$$

Finally, equation 20 is plugged into equation 5 and solved for α_{1new}.

$$\alpha_{1new} = \frac{2\theta(\alpha_2 - \alpha_1)}{\alpha_2(t_{target})^2} \tag{21}$$

Once α_{1new} is determined, equation 17 can be solved for α_{2new}.

$$\alpha_{2new} = \frac{\alpha_2 \alpha_{1new}}{\alpha_1} \tag{22}$$

Trapezoidal Profile

In order to calculate the trapezoidal profile, the change in time for the acceleration and deceleration periods needs to be calculated. These two changes in time sum to the total change in time Δt as calculated in equation 16.

$$\Delta t = \Delta t_1 + \Delta t_2 \tag{23}$$

Then, Δt_1 using equations 10, 17, and 23 can be solved

$$\Delta t_1 = \frac{\alpha_2}{(\alpha_2 - \alpha_1)} \Delta \mathrm{t} \tag{24}$$

For the trapezoidal solution, what is depicted in figure 3 is calculated. To do so, equation 2 is written using Δt_1 as calculated in equation 25.

$$\omega_{max} = \alpha_{1new}(t_1 + 2\Delta t_1) \tag{25}$$

The result for solving for a_{1new} is

$$\alpha_{1new} = \frac{\omega_{max}}{(t_1 + 2\Delta t_1)} \tag{26}$$

With a_{1new} solved, a_{2new} can be solved using equation 22 from the triangular profile solution.

RESULTS AND DISCUSSIONS

The calculations presented in this report were entered into a spreadsheet and various scenarios were simulated. The calculated motion profile values were then fed into models for the elevation actuator of an existing weapon system. The peak power values of the modified profiles were compared against the original profiles. For the original profile, acceleration and deceleration rates of 25 deg/s^2 were used with a maximum angular velocity of 20 deg/s. These values represent the elevation profile limits for the weapon system.

In figure 5, a displacement of 15 deg was performed. The original profile completed this motion in ~1.5 sec using a triangular motion profile. When the target time was extended to 4 sec, the acceleration and deceleration rates were decreased from 25 to 3.75 deg/s^2 with the profile remaining triangular.

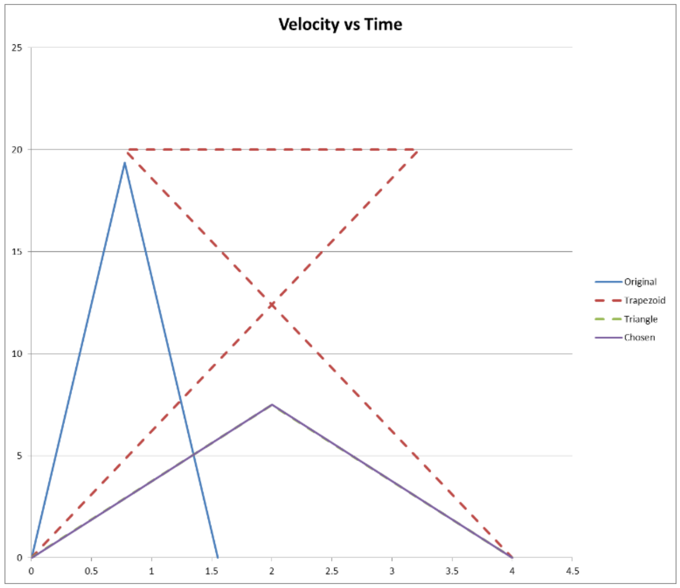

Figure 5
Simulation of 15 deg motion

In figure 6, a displacement of 45 deg was performed. The original profile took ~3 sec to complete. When the target time was extended to 4 sec, the rates were decreased to 11.25 deg/s^2. The profile began as, and remained, trapezoidal in shape.

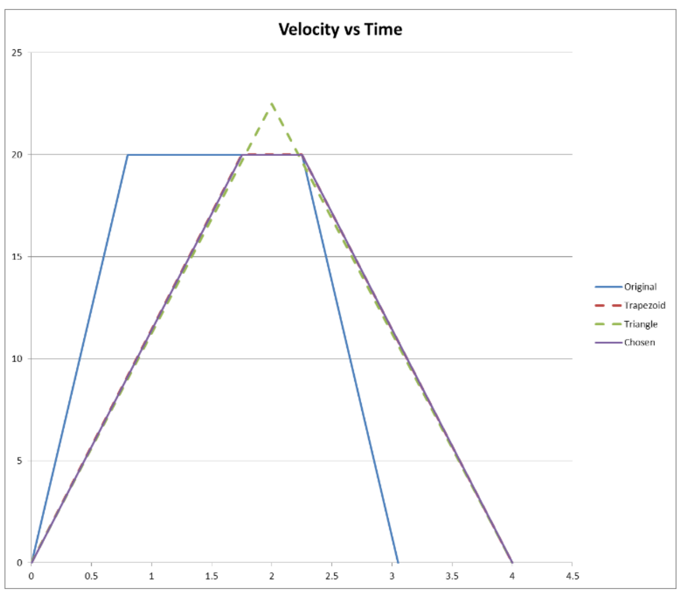

Figure 6
Simulation of 45 deg motion

In figure 7, the same displacement of 45 deg was performed, but the target time was extended to 8 sec. The new profile decreased its rates to 2.8 deg/s^2, and the resulting profile was transformed from trapezoidal to triangular.

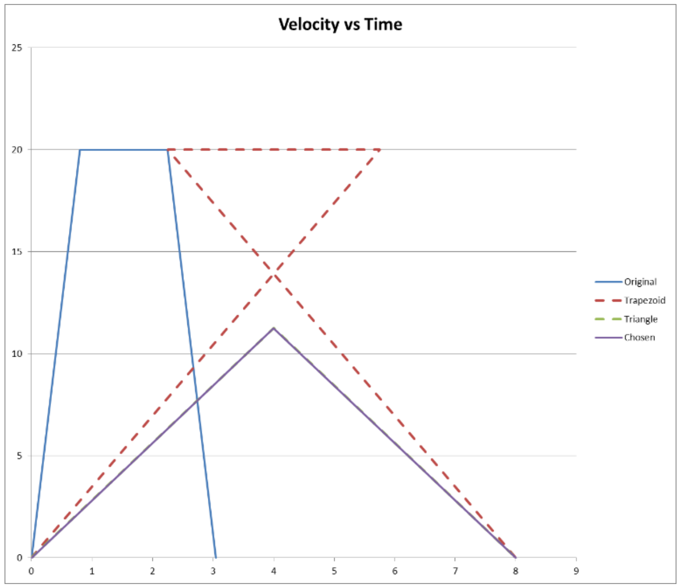

Figure 7
Simulation of 45 deg motion (extended)

Simulations of an existing system were performed and the following scenario was examined. The gun is pointing at 0 deg azimuth and 15 deg elevation. It gets a command to lay at 180 deg azimuth and 30 deg elevation. The travel times are calculated and compared. The traverse axis will take 8 sec to complete its motion using acceleration and deceleration rates of 20 deg/s^2 and a maximum velocity 28 deg/s. The elevation axis, using the same values as mentioned previously (25 deg/s^2 and 20 deg/s), would complete its motion in 1.55 sec. The traverse axis takes longer to complete and, therefore, becomes the new target time for the elevation actuator. Application of the algorithms described in this report resulted in a reduction of acceleration from the original 25 to 0.9375 deg/s^2. The peak power used by the elevation axis was reduced from 743 to 128 W. The azimuth power remains the same as its original profile is maintained.

Calculating the overall benefit to a particular system is difficult. The peak power is reduced as a function of the difference in travel times between the axes. If they take the same amount of time, no savings are realized. From a mechanical perspective, there is no energy savings, as the same amount of mechanical work is being performed regardless of the time taken to perform it. When the electrical components are taken into account, this is no longer the case. By lowering the acceleration, the torque required to perform the acceleration is also reduced. Mechanical torque is analogous to electrical current. Electrical conductors including wires, integrated circuits, motor windings, and printed circuit board traces have electrical resistance. That resistance restricts the flow of electricity and causes a reduction in efficiency in the form of its current squared multiplied by the resistance. This energy is lost as heat in the conductors themselves. Careful analysis of the specific conditions present in a given system may permit the use of smaller conductors, motors, electronics, etc.

CONCLUSIONS

The benefits of implementing the presented algorithm are clear. For a minimal overhead in calculation, the user can benefit from lower peak power use while still reaching the given target in the least amount of time. The time may even decrease slightly if settling times are reduced by the reduction in imparted forces caused by the acceleration decreases. These calculations are not limited to laying of weapon systems. They are equally applicable to other two axis systems such as gantry tables and pan tilt devices, etc.

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